Droplet characteristics and local equivalence ratio of reacting mixture in spray counterflow flames

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ABSTRACT

Spray combustion was studied by injecting monodisperse 125 or 200 μm ethanol droplets in a premixed natural gas fuel flame flowing against an opposed heated air jet. Phase Doppler anemometry and chemiluminescence measurements allowed to characterise both droplet parameters and the local reacting mixture. Both types of droplets crossed the flow stagnation plane and entered the opposite jet. However, 125 μm droplets reversed their motion and oscillated around the stagnation plane, leading to increased droplet residence time in hot regions. The fuel vapour released by droplets close to the stagnation plane, mixed with the surrounding air and led to the ignition of a second fuel vapour flame below the natural gas flame. For 125 μm droplets, mean local equivalence ratio of the fuel vapour flame was about 0.8, suggesting lean-premixed combustion; whereas 200 μm droplets led to stoichiometric combustion. "Group Combustion" number was estimated from measurements and suggested that 125 μm and 200 μm droplets burned in different "Group Combustion" regimes.

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1. Introduction

Early studies on liquid fuel combustion commonly associated droplet burning with non-premixed reaction mode [1], which leads to high flame temperature and, therefore, high levels of NO_x emissions. However, low-NO_x liquid-fuelled burners do exist and the NO_x reduction must be associated with some kind of partially-premixed combustion [2]. Indeed, droplet dispersion around the reaction zone in liquid-fuelled burners can affect droplet evaporation and some premixing of fuel vapour with air may occur prior to the ignition of a partially-premixed flame. Nonetheless, the relative contribution of premixed and non-premixed combustion in low-NO_x liquid-fuelled burners is usually unknown, as well as the equivalence ratio of the reacting mixture and both quantities can contribute to reduced NO_x emissions. Additionally, in an industrial-type combustor, it is difficult to determine the respective influence of each of these parameters. Consequently, in the literature, experiments used to better understand the fundamentals of spray combustion are often performed on idealised spray flames in order to minimize the coupling between the different effects and provide parametric results. Spray counterflow flames offer a stable reaction zone close to the flow stagnation plane with

constant strain rate and good optical access for non-intrusive measurements, and have been extensively used to study droplet combustion, either experimentally [3–7] or numerically [8–12]. They can be divided in two types: (1) all droplets evaporate upstream from the reaction zone or (2) some droplets cross the flame front and burn beyond it. The first case results in fully single-phase combustion [13–15], which is of little interest for industrial burners where most of the droplets do not evaporate completely before reaching the flame front. The latter case is more representative of real burners because it deals with two-phase flames. Indeed, this arrangement can simulate droplet dispersion and fuel vapour mixture formation around the reaction zone close to the stagnation region of a liquid-fuelled combustor stabilised by a recirculation zone. Two-stage spray counterflow flames were for example reported experimentally in [3,16,17] where single droplet burning beyond the main flame was observed with n-heptane or methanol, which are high-volatility fuels. More recently, Mikami et al. [18] could identify combustion of individual droplets or droplet clusters beyond the main flame in a counterflow burner operating with n-decane (i.e. a low-volatility fuel of interest for model gas turbines) and proposed a mechanism to explain transition from isolated droplet to cluster combustion. Two-stage counterflow flames (operating with different liquid fuels) were also reported in computational studies [9,10,19] and Continillo and Sirignano [9] have indicated that both premixed-like and diffusion-like combustion can occur in low-strained n-octane spray counterflow flames.

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Coexistence of both burning regimes was also observed numerically by Akamatsu and co-workers [11,12] in laminar n-decane spray counterflow flames and the influence of strain rate, overall equivalence ratio and droplet size was investigated. An additional interesting feature of two-stage spray counterflow flames concerns the possible occurrence of droplet oscillations around the burner stagnation plane which were first reported experimentally in [20] and later in [4,21]. Indeed, the authors mentioned that droplet oscillations could be associated with increased droplet residence time in the burner, which could yield increased release of fuel vapour in the flow and, subsequently, modify the local equivalence ratio. Later on, in highly-strained counterflow spray flames (fuelled with methanol, ethanol and n-heptane), extensive numerical studies by Gutheil and co-workers [10,22–25] have predicted the presence of a second maximum in the profiles of fuel vapour concentration and temperature along the burner axis, coinciding with the location where droplets reversed their motion. The authors have shown that the occurrence of multiple reaction zones depends on the flow strain rate, as well as on droplet size, albeit simulations were performed with monodisperse or bidisperse droplet sprays only. These numerical findings were a great source of inspiration for the present experiments.

It is noted that the experimental studies mentioned above quantified mainly droplet characteristics (i.e. size and velocity), but not flame properties (i.e. local equivalence ratio and degree of premixing). The purpose of the current work was, therefore, to perform experiments in spray counterflow flames with monodisperse droplets penetrating the flame in order to quantify the characteristics of the local reacting mixture and correlate them with droplet size. The remaining paper comprises three parts. The first part describes the experimental facility, the optical techniques used for the measurement of spray characteristics and local reacting mixture. The second part presents the results and discusses the findings in terms of "Group Combustion" theory. Finally, the paper ends with a summary of the findings.

2. Experimental set-up

2.1. Test facility

The counterflow burner used for this work (Fig. 1) was the same as that of [26] and similar to that of [27,28]. It comprised two opposed brass pipes with inner diameter $D = 30$ mm, separated by a distance $H = 25$ mm. Premixed gaseous fuel (natural gas with 94% methane) and air were injected from the upper duct, while only preheated air at 420 K was injected from the lower duct. Coaxial jets of N_2 could be operated on both sides, in order to prevent diffusion flames from appearing at the edges of the flat flames. The equivalence ratio of the premixed natural gas was kept constant at $\Phi_0 = 0.7$ and the bulk gas velocity was fixed to $V_0 = 2$ m/s (V_0 is the area-averaged velocity at the ducts exit). This corresponds to bulk flow strain rate of 160 s^{-1} and turbulent strain rate of 320 s^{-1}. The bulk flow strain rate was classically evaluated as $S = 2V_0/H$. The turbulent strain rate was obtained from measured local velocity fluctuations and an estimate of the turbulent length scale of the flow [26], following the definition of Mastorakos et al. [27]:

$$S_t = \frac{C_q^{3/2} V_0^{3/2}}{\sqrt{\nu L_t}} \tag{1}$$

where C_q is the normalised turbulence intensity ($C_q \sim 0.085$), L_t the turbulent length scale ($L_t \sim 3$ mm) and ν is the kinematic viscosity of air ($\nu = 1.59\mathrm{E}{-}5$ m^2/s at 300 K).

The injection of ethanol (99% purity) droplets in the counterflow burner was realised using a custom-made monodisperse
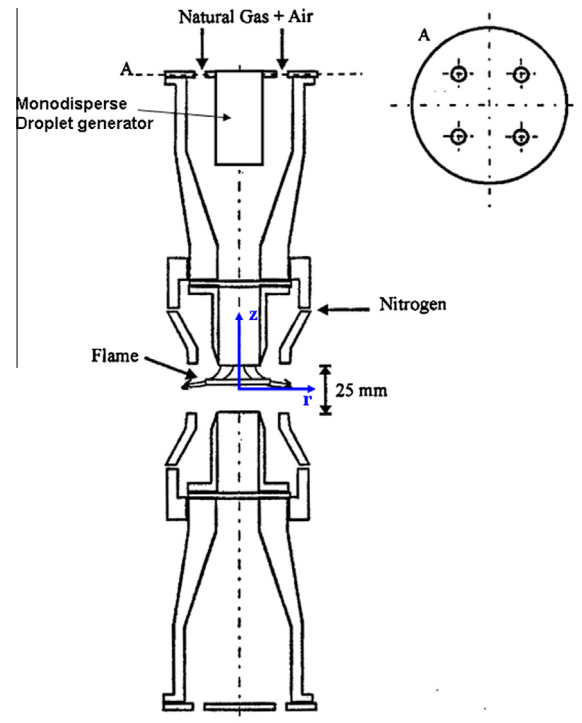

Fig. 1. Sketch of the counterflow burner fuelled with natural gas. The exit of the monodisperse droplet generator is located 120 mm from the stagnation plane.

droplet generator [29], located on top of the upper duct of the counterflow burner. The droplet generator was of similar type to that of Berglund and Liu [30]. It consisted of two piezoelectric transducers which imposed perpendicular vibrations onto a liquid jet passing through a pinhole (diameter: 50 or 100 μm). These vibrations yielded jet oscillations, which ultimately caused its break-up and led to a stream of monodisperse droplets which size was imposed by the pinhole diameter and the vibrations frequency. The droplet injection frequency was 20 and 10 kHz, respectively for the 50 and 100 μm pinholes, leading respectively to droplets with diameter 125 μm (velocity 8 m/s) and 200 μm (velocity 12 m/s). Liquid flowrate was 1.2 and 2.5 cc/min for 125 and 200 μm droplets respectively. A single stream of monodisperse droplets was injected along the symmetry axis of the natural gas/ air jet, at a distance of 120 mm from the stagnation plane of the counterflow burner. The droplet generator was water-cooled in order to maintain ethanol fuel at a constant temperature (298 K). Droplet sizes were selected, so that droplet evaporation upstream of the natural gas reaction zone was negligible.

The coordinate system used in the present experiments has its origin on the burner vertical axis at the stagnation plane, Fig. 1. Results will be presented as a function of the radial distance r normalised by the radius of the counterflow burner $R = 15$ mm and the axial distance z normalised by the distance between the two ducts of the counterflow burner $H = 25$ mm. Therefore, the value $z/H = 0$ corresponds to the flow stagnation plane, the upper duct of the burner is located at $z/H = 0.5$, while the lower duct is at $z/H = -0.5$. The value $r/R = 0$ corresponds to the burner vertical axis, the edges of the burner are located at $r/R = -1$ and $r/R = 1$.

2.2. Optical measurement techniques

In the literature, chemiluminescence from OH*, CH* and C$_2^*$ radicals has often been used to determine the flame front structure [31,32] or to monitor heat release [33,34]. Additionally, correlation